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ALTERNATIVE CARTRIDGE CASE MATERIAL AND DESIGN

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Armaments Engineering and Technology Center (Benet)

Picatinny, New Jersey

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14. ABSTRACT
Today's soldiers carry 92 to 105 lbs of mission essential equipment into combat. This overload causes fatigue, heat stress, and injury. Every soldier has to carry ammunition. A lightweight cartridge case would reduce the burden of the soldier. Frontier Performance Polymers Corporation addressed novel ways of designing a light-weight polymer cartridge case. In this report, Frontier Performance Polymers designed several plastic cartridge cases, conducted finite element analysis, failure analysis, addressed the high heat of the chamber, the material properties of polymers in its designs of the 5.56-mm cartridge case.

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ABBREVIATIONS AND ACRONYMS

Term	Definition
ABS	Acrylonitrile Butadiene Styrene polymer
ACM-AT	Frontier's advanced case material
COF	Coefficient of friction
HDPE	High-density polyethylene
HTN	High temperature nylon
LCP	Liquid crystalline polymer
Noryl GTX	Poly(phenylene ether) and polyamide blend and is a registered trademark of General Electric
PA	Polyamide
PA11	Polyamide 11
PA12	Polyamide 12
PA46	Polyamide 4,6
PA6	Polyamide 6
PA66	Polyamide 6,6
PA6T	Polyamide 6 and 6T co-polymer
PAI	Polyamideimide
PAR	Polyarylate
PBT	Poly(butylenes terephthalate)
PC	Polucarbonate
PEI	Polyetherimide
PEEK	Poly(ether ether ketone)
PES	Polyethersulfone
PET	Poly(ethylene terephthalate)
PP	Polypropylene

Abbreviation and Acronyms
(continued)

PPA	Polyphthamide
PPE	Poly(phenylene oxide) or poly(phenylene ether)
PPS	Poly(phenylene sulfide)
PSU	Polysulfone
PTFE	Poly(tetrafluroethylene)
Tg	Glass transition temperature
Tm	Melting temperature

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BACKGROUND AND INTRODUCTION

Background

Advances in weapon systems have resulted in the soldiers carrying additional gear to enhance combat effectiveness, but at the cost of increased weight. Today, soldiers on combat patrols in Afghanistan typically carry 92 to 105 lbs of mission essential equipment, which includes extra ammunition, chemical protective gears and cold-weather clothing. This overload causes fatigue, heat stress, injury, and performance degradation for soldiers. To ensure that America's soldiers maintain their overwhelming combat edge into the 21st century, making the load lighter for soldiers has moved to the top of the priority list in the Army. The focus of the Lightweight Family of Weapons and Ammunition (LFWA), a Joint Service Small Arms Program (JSSAP), effort is to lighten the load. In fact, one of the heaviest pieces of load for a soldier may be the ammunition.

Despite years of research and development, the Army's weapons and equipment is still too heavy, to allow foot soldiers to maneuver safely under fire. Every solider has to carry a lot of ammunition during combat, for example, the weight of caliber 0.50 ammunition is about 60 lbs per box (200 cartridges), but it is burdensome for a soldier to move around with heavy ammunition aside from carrying additional gears at the same time. Conventional cartridge cases for rifles and machine guns, as well as larger caliber weapons are usually made with brass, which is heavy and expensive. The need for an optimal solution that can increase mission performance, operational capabilities, and affordability is a material to replace the brass.

In order to achieve the desired lethality with a lighter load and to reduce ammunition requirements, the only way to fully realize the lightweight concepts is to look at novel ways of designing the system such as allowing the use of lightweight polymers as the cartridge case material, which would alleviate a portion of this weight burden. As early as 1960, the U.S. Military has recognized the benefits of using polymer or polymer composite for cartridge case applications, and since then many research efforts have been carried out by the military and ammunition industry. The earlier studies only demonstrated the feasibility and did not achieve consistent and reliable ballistic results. Recent efforts have focused on a metal and plastic hybrid cartridge case design. On the other hand, most civilian development efforts went into low-pressure and low muzzle-velocity cartridge case applications. No long-term reliability study was done.

Challenges

Affordability and performance of ammunition case material have become key factors in lightweight cartridge case development. In order to select a proper plastic material for the ammunition cartridge case application, one has to first recognize the significant differences in mechanical, physical, and chemical behavior between plastics and brass. Most plastic materials, even with a high glass fiber loading, have much lower tensile strength and modulus than brass. Tensile strength of brass is 50 to 75 Kpsi versus 10 to 40 Kpsi of plastics, and Young's modulus of brass is 30,000,000 psi versus 200,000 to 3,000,000 psi of plastics. Therefore, when selecting a plastic material to replace brass for the cartridge case application, it is important to first identify the key performance requirements for the case, and then consider how to overcome the inherent weakness of the material through case design to meet or exceed the performance requirements.

The lightweight polymer cartridge must be capable of surviving the physical and natural environment in which it will be exposed during the ammunitions intended life cycle along with meeting the reliability and performance of existing fielded ammunition. The existing polymer/ composite case technologies have many shortcomings such as insufficient ballistic performance; cracks on the case mouth, neck, body and/or base; bonding failure of the metal-plastic hybrid case; difficulty of extraction from the chamber; incompatibility with propellant – particularly for double-base propellants; insufficient high temperature resistance – burned holes, and thicker case wall requirements. The technology breakthroughs in cartridge case design and performance polymer materials are in demand.

FAILURE ANALYSIS OF EXISTING POLYMER AMMUNITION CARTRIDGE CASE

Common product failures when using plastic material to replace metal can usually be divided into three discrete arenas: improper design, improper manufacturing (including processing and assembly), and improper material selection. Therefore, investigating the potential failure mechanisms and identifying their root causes are very critical for product improvements to successfully apply lightweight polymer materials to replace the heavier metals for existing applications.

After reviewing reports from past polymer case developments, studying their failure modes and investigating the failure mechanisms, the principal investigator identified the potential root causes and concluded that the Failure Modes and Effects Analysis (FMEA) can be categorized into three types: (1) during ballistic cycle; (2) during case loading, extraction, ejection, and cook-off; and (3) long-term reliability and fabrication. The details are summarized in the following sections.

During Ballistic Cycle

Failure mode (What's gone wrong?)	Consequences (effect of failure)	Root cause
Excessive movement of the primer has occurred after being struck by the firing pin	Failure to ignite the primer	Polymer does not have sufficient rigidity to support the primer from movement
Cracks at the case mouth or neck area, or the case neck is completely shattered	Poor ballistic performance due to gas leak	1. Polymer material lacks ductility. 2. Inaccurate tolerance or clearance caused by improper mold or case design.
Cracks at the case head, wall, and neck	Poor ballistic performance due to gas leak	1. Improper material selection (lack of ductility or strength). 2. Inadequate case design (thickness variation, weak joints, etc.). 3. Improper mold design (wrong gate location, excessive molded-in stress, etc.).

Failure mode (What's gone wrong?)	Consequences (effect of failure)	Root cause
Cracks around the primer hole caused by the force from exploding primer or burning propellant	Poor ballistic performance	1. Polymer does not have sufficient rigidity to prevent the primer from movement. 2. Improper mold design.
Burn holes are created on the case	Poor ballistic performance	Temperature resistance of polymer is too low
Loss of large interior volume due to the thicker case wall	Poor ballistic performance	1. Inadequate case design results in excessive wall thickness. 2. Limited by injection molding process.
Case cracks or shatters when it is tested at -65°F	Poor ballistic or gun malfunction	Polymer has poor low temperature ductility
Propellant gas leaks at the bullet holder	Poor ballistic performance	Improper bullet holder design

During Case Loading, Extraction, Ejection and Cook-Off

Loading

Failure mode (What's gone wrong?)	Consequences (effect of failure)	Root cause
Cracks at the case neck area	Poor ballistic performance, which may cause the gun to malfunction	1. Polymer does not have sufficient impact resistance. 2. Inadequate base design (insufficient rigidity in the next area).

Extraction & Ejection

Failure mode (What's gone wrong?)	Consequences (effect of failure)	Root cause
Case body separated from the case base after cook-off	Cause the gun to malfunction	1. Improper metal-plastic hybrid case design results in low strength. 2. Fabrication variations. 3. Improper material selection.
Plastic residue stays in the chamber	Cause the gun to malfunction	Polymer has too low temperature resistance
Ejector stuck in the case head	Cause extraction failure	Polymer has insufficient heat distortion temperature and rigidity

Failure mode (What's gone wrong?)	Consequences (effect of failure)	Root cause
Extractor fails to extract the spent case or damages the extraction groove of the case head	Cause the gun to malfunction	Improper material selection of the case head

Cook-Off

Failure mode (What's gone wrong?)	Consequences (effect of failure)	Root cause
Case head and body separation	Cause the gun to malfunction	1. Polymer has too low temperature resistance 2. Improper design results in low pull strength at cook-off temperature 3. Polymer has too low tensile strength at cook-off temperature

Long-term Reliability and Fabrication

Long-Term Reliability

Failure mode (What's gone wrong?)	Consequences (effect of failure)	Root cause
Incompatible with propellant	Long-term reliability problems	Improper material selection
Excessive moisture absorption on propellant and dimensional changes over time	Long-term reliability problems and poor ballistic performance	1. Improper material selection (poor moisture barrier, poor stress cracking resistance, etc) 2. Poor long-term reliability of mechanically fastened joint of metal-plastic hybrid case design 3. Stress relaxation in the case mouth
Adhesive or mechanical joint failure on the metal-plastic hybrid case design	Long-term reliability problems and poor ballistic performance	1. Stress relaxation or creep from mechanical joint 2. Stress from thermal cycle due to thermal expansion coefficient difference between metal and plastic 3. Moisture effect on the adhesive

Failure mode (What's gone wrong?)	Consequences (effect of failure)	Root cause
Cracks at the case during storage due to stress cracking	Long-term reliability problems and poor ballistic performance	1. Improper material selection (poor aging resistance, poor stress cracking resistant, poor chemical cracking resistance, etc) 2. Inadequate case design that incorporates excessive stress in the case body

Fabrication

Failure mode (What's gone wrong?)	Consequences (effect of failure)	Root cause
Insufficient bullet pull force	Poor ballistic performance and long-term reliability problems	1. Improper material selection 2. Improper case mouth design
Case deforms excessively during case insertion	Cause the case to distort around the shoulder and neck area	1. A high bullet insertion force is needed 2. Improper material selection 3. Improper bullet holder design
Potential defects in the bonded joints of the hybrid case design	Long-term reliability problems	Making consistent adhesive bonded, mechanical bonded or welded joint is very challenging for a large volume production

Why Most Polymer Cases Fail

After carefully reviewing and summarizing all the failure modes and their corresponding root causes of the failures seen in the past polymer ammunition cartridge case developments, the principal investigator concluded three major root causes including polymer lack of ductility, polymer does not have sufficient temperature resistance, and improper case design or fabrication are the common problems seen in the past polymer development reports for small caliber tactical weapon applications:

Major Root Causes	Failure Modes
1. Polymer lacks of ductility - This is the most often seen root cause for the past polymer case development programs - It is still the major issue for current polymer case developments	• Crack on case mouth • Longitudinal case split • Circumferential case crack of separation • Case shatter at low temperature

Major Root Causes	Failure Modes
2. Polymer does not have sufficient temperature resistance - This is a major problem when using the existing polymer case for assault rifle applications due to its close bolt design	• Burn hole seen after firing • Case separation after cook-off and can not be extracted out of gun chamber
3. Improper case design or fabrication - Design insufficiency - Solely relies on the small interference occurred from the snap-fit to provide all the pull strength - Improper gate locations - Improper molding conditions	• Case separation during extraction • Case separation after cook-off • Case crack or split caused by weak weld line • Excessive molded-in stress may cause long-term storage issues

To make a polymer case successful for tactical assault rifle applications, the case design and material selection have to address these three major root causes. On the whole, Frontier's innovative case design combined with its proprietary polymer materials will overcome these three root causes and make the polymer case a reality, which will propel the Army into the 21st century.

REVIEW OF COMMERCIAL POLYMER MATERIALS FOR TACTICAL AMMUNITION CARTRIDGE CASE APPLICATION

Military ammunition cartridges have to perform well and reliably in extreme environments and/or after long-term storage in hazardous environments. The stringent long-term performance requirements in all weather have placed burdens on the material selection. Even though the conventional brass case has many shortcomings, it has been proven functional and reliable to meet the military stringent demands. For instance, the mechanical properties of the brass material, after being hardening or heat-treated, change little with a temperature from -65°F to 800°F. In contrast, the property of the polymer is highly sensitive to temperature. This is because a polymer is a higher molecular weight organic compound with a limited temperature resistance. The upper application temperature limits of the polymer is determined by its glass transition temperature or melting temperature. The polymer can start melting and losing all mechanical strength when it is exposed to a temperature that exceeds its melting point (for semi-crystalline type polymers) or glass transition temperature (for amorphous type polymers). Moreover, almost all polymer materials start to degrade at a temperature above 400°C (or 750°F) and eventually completely decompose to CO_2 and H_2O, if it stays at this high temperature long enough. The upper application temperature limit of the polymer is the inherent characteristics of the polymeric material and can not be altered without changing the material selection. Adding reinforcements, such as glass fiber or carbon fiber, into the polymer can boost up its strength and modulus, but will not change the upper application temperature limit of the polymer. Therefore, the material selection for the ammunition cartridge case application has to tie closely to the expected temperature inside the chamber of military weapons.

On the other hand, the ductility of the polymer, including impact resistance and extensibility, decreases as the temperature decreases. It has been known that the ductility of the polymer is controlled by the mobility of either the polymer chain backbone or side chain molecules. The mobility of the polymer chain backbone can be identified as "α transition" which is also known as the glass transition, while the mobility of the side chains is identified by "β or γ transition". As the temperature decreases, the mobility or polymer backbone or side chains can eventually cease, thus the polymer losses it ductility. This temperature is known to be the ductile-brittle transition temperature of the polymer.

It is a challenging task to select a polymer system for tactical ammunition cartridge case applications, which are required to survive the ballistic pressure of the military weapons. Moreover, it is a more difficult task indeed to select a polymer that can sustain the pressure of being at the extreme low temperature of -65°F all the way to the cook-off temperature of 420°F or higher.

Polymer Materials Used in the Past Developments

After reviewing the polymer materials used for cartridge case development during the past 60 yrs, the principal investigator found that almost all the engineering plastic materials have more or less been evaluated for tactical ammunition cartridge case applications, which includes either unfilled glass fiber or filled with LCP, PAI, PA66, PA612, PA12, PC, PEI, Noryl GTX, PP, HDPE and ABS. Despite that various materials were tested, none of them achieved satisfactory results for the military application. Most common failures from the past evaluations of polymer cartridge case material are cracking, splitting, extrusion, and failure to extract. Table 1 lists the primary materials used in the polymer ammunition cartridge case application, their corresponding programs and the results from the past development efforts.

Table 1
Summary of past material evaluation for polymer ammunition cartridge cases

Primary material	Program	Results	Comments
Glass fiber filled Zytel with ST-801 (super tough PA66)	Ongoing 5.56-mm two-piece plastic-plastic design	• Crack found after firing	• Limited information is known
Parmax	5.56mm and .50 caliber	• Case cracked at the case base tested on AR-15	• Changed the case design from all-polymer to two-piece brass-polymer design
Super tough PA612	Ongoing 5.56-mm brass- plastic design	• Failed to extract after cook-off • Shattered after firing @ -65°F • Cracks found during firing on commercial chamber	• Partial melting on the plastic body was observed
Noryl GTX-910 (PPE and PA66 blend)	Telescope case design by ARES for ACM program	• Cracks found after firing at 140°F • Circumference cracks and case split occasionally observed • Degraded performance and extrusion in hot humid environment	• Material showed extrusion

Table 1
(continued)

Primary material	Program	Results	Comments
PA12 or PP	Telescope 5.56-mm flechette round for ACM program	• Failed to eject due to extrusion of the polymer case, it occurred particularly in hot or rainy weather when the polymer became softer • Circumference cracks observed in the primer ring area • Case shattered at the temperature of 5°F or lower • Case rupture caused crack on butt-stock	• Material showed extrusion
HDPE	Blank .50 caliber	• Low impulse at 0°F caused extraction problems • Material showed stress cracking	• HDPE has very low temperature resistance
GF filled PA12	25-mm telescope case by Brunsewick and 5.56-mm M855	• Case cracked and split	
Unfilled PA12	20 mm and 30-mm Aluminum-plastic hybrid	• Snap-fitted the plastic case body onto aluminum case head • A rubber cup was inserted from the mouth to protect the aluminum case head • Cracking and splitting were seen at the case mouth	• The design concept is very interesting and achieve more than 30% weight saving • The rubber seal cup was found to be difficult to reliably insert • Poor material selection
GF filled Nylons, polyester and PC	5.56-mm blank with metal retainer	• Glass fiber filled nylon and polyester performed unsatisfied, but 10%GF PC performed OK • Working OK but showed some cracking and extraction issues • Occasionally case split and failed to extract	• PC was not compatible with propellant • Case cracked and split • Extraction issue

Material Performance Targets for Ammunition Cartridge Case Applications

Based on his review and analysis of all the failure mechanisms of the past development of tactical ammunition cartridge cases, the principal investigator has identified the following three crucial material parameters as criteria for the material selection:

- Propellant compatibility and chemical resistance
- Upper temperature limit
- Ductility or elongation-to-break at high strain rate

Criterion A - Propellant Compatibility and Chemical Resistance

First and foremost, the key polymer material characteristic needed for the ammunition cartridge case application is its resistance to the propellants and chemical agents, which it may encounter during its service lifetime. Typical ball propellants used in military small-arm ammunitions are comprised of the following key ingredients:

Nitrocellulose 75-85%
Nitroglycerin 6-15%
Dibutylphthalate 2-8%

These ingredients used in the propellants have been known to potentially cause physical aging, or act as plasticizer for some polymers, or lead to chemical degradation that result in losing their ductility or strength. The principal investigator summarizes the propellant compatibility of polymers and their root causes from the past reports in table 2.

Table 2
Reported propellant compatibility of selected polymers

Polymer system	Propellant compatibility	Root cause and remarks
PA6,6	Compatible	Excellent chemical resistance
HDPE	Compatible	Has been used in commercial ammunitions
ABS	Incompatible	May cause swelling from absorbing the ingredient and loss of its strength
PC	Incompatible with double base propellant	Caused thermal aging and loss of its ductility
PEI	Not known	Has been used in .50 caliber for sabot applications
Acetal	Incompatible	Caused chemical attack and loss of its strength

Other than the propellant compatibility, the polymer used for ammunition cartridge cases also needs to have good resistance to many chemicals encountered in military applications. Besides the greases and oils commonly used for cleaning weapons, military ammunition also must resist many chemicals used in the current warfare, such as chemical, biological, and radiological agents.

In general, the crystalline lattice of the semi-crystalline polymers provides a good barrier against chemical attack, so that the semi-crystalline polymers have better chemical resistance than the amorphous polymers. Therefore, the material selection for the ammunition cartridge case applications is focusing on the use of the semi-crystalline polymers. Nonetheless, some of the high temperature amorphous polymers, such as polyetherimide (PEI), polyethersulfone (PES) and polyamideimide (PAI), have been proven to have better chemical resistance than conventional amorphous polymer and shall also be considered as the candidate material.

Criterion B - Temperature Resistance of Polymer

Another important criterion for selecting the polymer material for ammunition cartridge case applications is its upper temperature limit. The upper temperature consideration is depending on whether or not the polymer cased cartridge will be used on an assault rifle or machine gun or both.

The gas temperature from military high power propellant firing can be 1000°F or higher, and some of the heat from the hot gas is transferred through the chamber and barrel to the entire metal block. The heat eventually dissipates to the air from the outer surface. Therefore, the temperature of the gun chamber depends on the number of rounds of ammunition that was fired in a short period of time. According to the studies conducted by the Armament Research, Development and Engineering Center (ARDEC), Picatinny, New Jersey, the barrel temperature of a machine gun can easily exceed 800°F after rapidly firing 500 rounds of ammunition. At this temperature, the polymer will quickly melt and lose its integrity and strength. However, due to the low heat conductivity of organic polymers and the very short resident time (0.05 sec of less) of the cartridge inside the hot gun chamber, the polymer cartridge case does not experience high temperature at all. This observation can be confirmed from past development of a blank .50 caliber polymer cartridge case made of high density polyethylene (HDPE). Even though HDPE has a low melting temperature (135°C), it had no problem meeting the performance requirements. Therefore, the upper temperature limit of the polymer is not a critical concern in selecting a polymer system for a polymer ammunition cartridge case used solely for machine gun application.

On the other hand, the upper temperature limit of the polymer will be a critical factor in selecting the polymer system for ammunition cartridge case applications for assault rifles. Military assault rifles are designed for readiness and will have a cartridge sitting in the gun chamber at any moment. There is a possibility of the polymer cartridge case being exposed to high temperature, which will equilibrate the case with the chamber temperature. The case made of a polymer with an insufficient temperature limit will melt, lose its strength and stick in the gun chamber, which results in extraction failure and gun malfunction. Therefore, identifying the chamber temperature of the assault rifle is vital in selecting a polymer system.

ARDEC has attempted to determine chamber temperature by using an infrared detector to measure the outer surface temperature of the gun barrel, and by inserting a cartridge with a thermocouple imbedded inside it after rapidly firing 209 rounds of ammunition. The result of this investigation suggests the chamber temperature is around 305°F or 152°C as shown in figure 1. However, ARDEC recognized the shortcoming of this measurement technique, by loading a cold brass cartridge case into the hot gun chamber, which underestimated the actual chamber temperature.

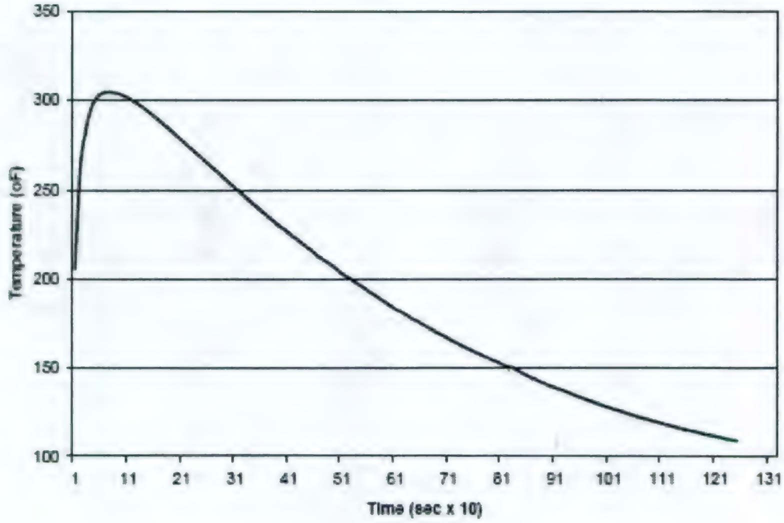


Figure 1
Temperature inside the M4 gun chamber after rapidly firing 209 rounds

After reviewing many test firing results done by ARDEC, the principal investigator estimated that the chamber temperature of a M4/M16, after rapid firing 200 to 300 rounds of ammunition, would be from 200° to 250°C (392° to 482°F) and can reach 250° to 300°C (482° to 572°F) after continuously firing 300 to 400 rounds of ammunition. Therefore, the selection of the polymer material for tactical ammunition cartridge case applications needs to identify a polymer system that has an upper temperature limit at least more than 250°C (482°F) or preferably above 300°C (572°F).

Criterion C - Elongation-to-break or Ductility

In the principal investigator's opinion, the third most important criterion for selecting the polymer system for tactical small caliber ammunition cartridge case applications is the elongation-to-break or ductility of the polymer. For example, in the past development of blank .50 caliber plastic cartridge cases, polyethylene was proven to survive well in ballistic pressure without the cracking or case splitting consistently seen in other polymer materials used under other programs. This may be due to the fact that polyethylene has excellent ductility even at -65°F, while most polymer materials tested before did not have the ductility even at the ambient temperature. Based on Frontier's finite element analysis effort to simulate the deformation on the 5.56-mm polymer cartridge case, it is estimated that the elongation-to-break of the polymer needs to be higher than 50% depending on the tensile strength of the polymer.

The fact of the need for heat treatment on the case mouth end of the M855 brass case to prevent the case from cracking or splitting confirms the importance of selecting a material whether metal or polymer with the high ductility for tactical ammunition cartridge case applications. The heat treatment process on the brass significantly lowers its tensile strength from 100,000 psi down to 35,000 psi, but it also drastically improves its elongation-to-break from 3 to 5% to 50%.

Through reviewing the past polymer ammunition cartridge case development, the principal investigator discovered that many past failures, such as the case splits in the mouth or shoulder areas and circumferential cracks in the case body just below the shoulder, are due to the poor ductility of the polymer material used. Not to mention that almost all of the bottleneck shape polymer ammunition cartridge cases shattered into many small pieces when they were fired at -65°F.

During the past two decades, the material development effort in the plastic industry has been focused on developing high impact resistant materials for automotive and consumer applications. This effort has led to the development of various "super tough" materials and their impact strength can be quantified by the high energy consumed to fracture a pre-notched specimen as being known as notched Izod or Charpy impact test. About 10 years ago, the principal investigator discovered that ductility and impact strength of the polymer are different matters and are involved in different deformation mechanisms. Therefore, a ductile polymer does not necessarily possess a high impact strength, and vice versa. A typical example of the relationship between the impact strength and elongation-to-break of an unmodified PA612 (Zytel 151) and a super tough PA 612 (Zytel FE-8194) at various temperatures and relative humidity conditions can be seen in table 3. The results in table 3 reveal that even though the impact modification of the super tough polymer has significantly increased the notched Izod impact strength of PA612, it does not affect its elongation-to-break. Hence, the super tough PA612 may not be a good candidate material for polymer cartridge case.

Table 3
Key properties of unmodified and super tough PA612

	Dried as molded	50%RH	100%RH
Elongation-to-break @ 73°F			
Unmodified PA612	30%	40%	50%
Super tough PA612	50%	50%	50%
Elongation-to-break @ -65°F			
Unmodified PA612 (ξ)	<10%	<10%	<10%
Super tough PA612 (ξ)	<10%	<10%	<10%

(ξ) The low elongation-to-break at -65°F resulted in the specimen shattered into many small pieces.

The main difference between ductility and impact resistance of the polymer is related to the deformation mechanism. The notched Izod impact involves energy absorption through localized yielding and the formation of crazes or multiple micro cracks around the crack tip, while the polymer needs to undergo a large scale of yielding such as necking to achieve a good ductility. It was well studied and known in the plastic industry that the high impact strength of the polymer can be effectively achieved through adding reactive rubbery impact modifiers. However, it is more difficult to increase the elongation-to-break of the polymer, since it has not been extensively studied by the industry, and requires more advanced modification techniques to increase the ductility.

POLYMER AMMUNITION CARTRIDGE CASE DESIGN FOR TACTICAL WEAPONS

Review of Past Polymer Cartridge Case Development

Driven by weight savings, many polymer and composite cartridge case designs have been proposed, simulated, or tested for military and civilian applications during the past 60 yrs. Due to the failures in the early all-polymer military small-arm ammunition cartridge case development, many of these cartridge cases were made by a metal-polymer hybrid design. The two-piece metal-polymer hybrid cartridge case design is a metal case base adhesive or mechanically bonded to a plastic case body. During his review of the U.S. patents on the telescope ammunition cartridge and reports related to Advanced Combat Rifle (ACR) development, the principal investigator discovered many interesting design concepts. Table 4 identifies some of the polymer ammunition cartridge case design concepts, their key features, and deficiencies from test firings.

Table 4
Selected polymer cartridge case designs, their features and deficiencies from the past polymer cartridge case development efforts

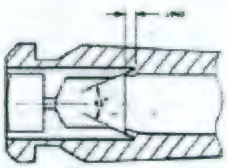
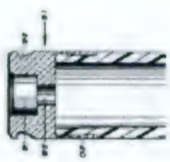
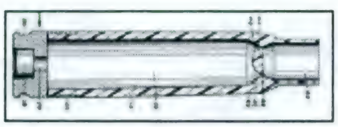
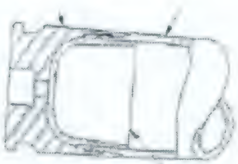
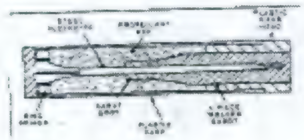
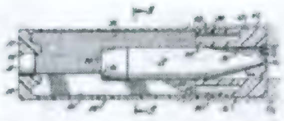
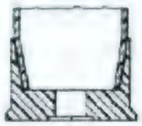
Case design	Unique features	Failure Modes and Deficiencies
	• Used metal retainer to reinforce the unsupported areas • Used 10% glass fiber filled PC	• Lost more than 30% of interior volume • PC material was found to be incompatible with propellant • Had many problems, such as splitting, case jam, observed during test firing
	• Adhesive was used to joint case head with case body	• Showed 10-20% lower muzzle speed • Adhesive was not reliable to bond plastic case body with brass case head
	• Two-piece design with snap-fit to mechanically joint the plastic case body with brass case head • Bullet was molded in place with bullet seat design to reinforce the case shoulder areas • Used impact modified PA612 for case body	• Failed to extract after cook-off • Case shattered at -65°F • Case splits were observed in commercial gun chamber • Circumferential crack were seen • Used 50%GF PA12 for case body
	• Used the rubber seal to prevent the aluminum from burning through	• Case cracked and split • Aluminum head failed

Table 4
(continued)

Case design	Unique features	Failure Modes and Deficiencies
	• Aluminum-plastic hybrid with snap-fit 5.56-mm Flechette case design is similar to other metal-polymer hybrid design • Used 50% glass filled PA12 for case body	• Case cracked and split
	• 5.56mm polymer cased Flechette design	• Flag formation due to the flow of the plastic material
	• Developed by ARES for ACR program and .50 caliber • Telescope case design with internal bullet support and no extraction groove • Used ultrasonic welding to weld cap with case body • Used Noryl GTX (PA/PPA Blend) or glass fiber filled PC material	• Circumferential cracked formed at 140°F • Degraded performance, crack and extrusion seen at 115°F and 85°F
	• Designed for 50 caliber blank ammunition cartridge, although drawing is for ball round • Used PE material for case body	• Lost more than 20% of interior volume • Stress cracking in PE case body occurred during storage • No report of case cracking • Tendency to blow the nose off (blank .50 cal design) at low temperature
	• Two-piece all-polymer design • Spin welding jointed both component together	• Designed for low pressure shot gun • Would not survive under the pressure of typical military tactical cartridge
	• Three-piece all-polymer design	• Designed for low pressure shot gun • Would not survive under the pressure of typical military tactical cartridge

Review of Brass M855 Case Design

Brass cartridge cases have been used for more than 100 yrs. Despite its shortcomings, the brass case has been the most popular choice for most weapons. Therefore, it is worthwhile to first understand the brass cartridge case design and how it performs during the ballistic cycle.

The brass M855 case design has a tapered contour that allows it to be extracted easily from the firing chamber after firing. While the brass cartridge case of a conventional round typically undergoes some permanent deformation, specifically radial expansion as a result of the

pressures developed during firing, the tapered design allows the spent case to be removed from the firing chamber with minimal resistance once the initial breakaway force is overcome. This tapered contour is also beneficial to polymer cased cartridge development, since polymers typically have a lower tensile strength than brass. The combination of the tapered shape and low coefficient of friction between polymer and steel will reduce the force for pulling the spent polymer case out of the gun chamber.

One of the most important developments for military small caliber ammunition cartridge case is the surface hardness gradient as shown in figure 2. The mechanical properties, such as tensile strength, of brass material can be tailored by mechanical hardening or heat treatment. For brass, a high hardness means a high tensile strength and high Young's modulus, which results in a low elongation. On the other hand, a low hardness means a high ductility and high elongation-to-break, but also results in a low tensile strength and Young's modulus. The concept of the hardness gradient of the brass material across the case through heat treatment is fantastic, because it allows the case to have strong material at the case head, which is unsupported inside the gun chamber and to have ductile material at the high strain areas, such as shoulder and mouth. The finite element analysis results confirmed that the deformation for the M855 brass case at the shoulder area could be as high as 30 to 40%.

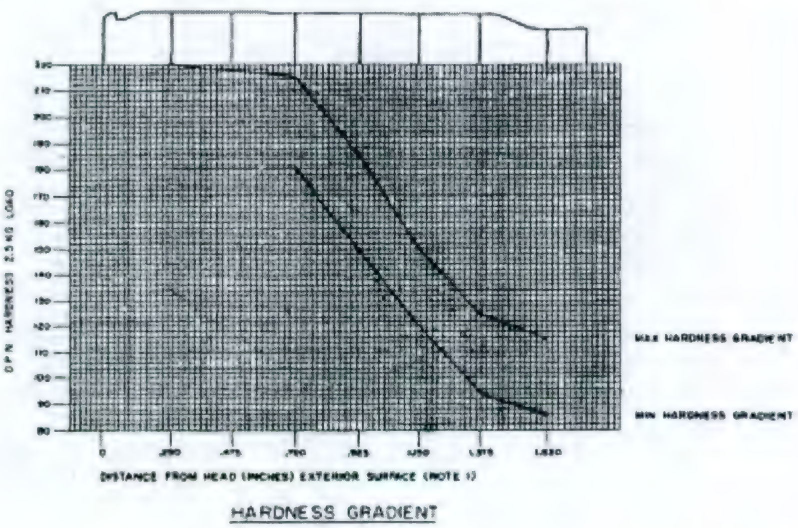


Figure 2
Surface hardness gradient of M855 brass cartridge case

In addition, when using brass cases on existing weapons, one needs to consider another important design factor, which is the tolerance between the exterior dimension of the brass case and gun chamber. By comparing the drawing of the M855 cartridge and gun chamber [the drawing of gun chamber was obtained from Sporting Arms and Ammunition Manufacturing Institute (SAAMI)], the nominal and worst scenarios of the clearance between the cartridge and gun chamber are shown in table 5. The strains on the case material at head end, shoulder end, and case mouth are also calculated assuming the case will expand to match the internal surface of the gun chamber under the interior ballistic pressure. Nevertheless, the macroscopic strain, as shown in table 5, does not reflect the actual strain that may be encounter in the case neck, shoulder, and mouth areas due to localized deformation, which may cause much higher strain at specific locations during deformation under ballistic pressure.

Table 5
Clearance between the M855 cartridge and M16 gun chamber at nominal and worst scenarios

Location	Head end		Shoulder end		Case mouth	
Scenario	Nominal	Worst	Nominal	Worst	Nominal	Worst
Case dimension	0.3759	0.3709	0.3543	0.3493	0.2480	0.2440
Chamber dimension	0.3769	0.3754	0.3547	0.3532	0.2540	0.2560
Clearance	0.005	0.0022	0.0005	0.0022	0.0030	0.060
Strain	0.27%	1.21%	0.28%	2.29%	2.42%	4.92%

Strength Versus Ductility – Determine the Key Design Criterion

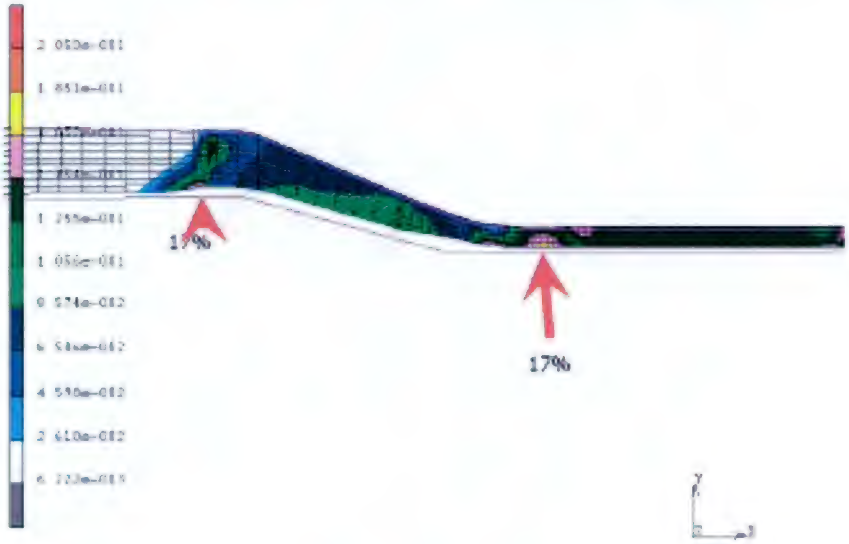
When selecting a polymer system for polymer ammunition cartridge case application, there is always a big question: whether to choose a high strength material or a ductile material. Unlike metal, polymer does not show significantly work-hardening or heat treatment effect to drastically change its strength or ductility. Moreover, too much stress hardening on polymer may increase its strength in its force direction, such as fiber drawing, which significantly weakens its strength in the transverse direction.

Ideally, a polymer for polymer case application needs to be as strong as a hardened metal and as ductile as a heat treated metal, particularly for the conventional bottleneck type 5.56-mm case, which has a large unsupported area. Unfortunately, while polymer scientists have yet to discover such a polymer, it may not be possible after all. Therefore, material selection criterion has to be focused on either strength or ductility, and then uses design to overcome its inherent drawbacks. This approach has been commonly practiced for selecting polymers to replace metals for automotive components and has made significantly contributions to reduce the weight of automotive vehicles in the last two decades.

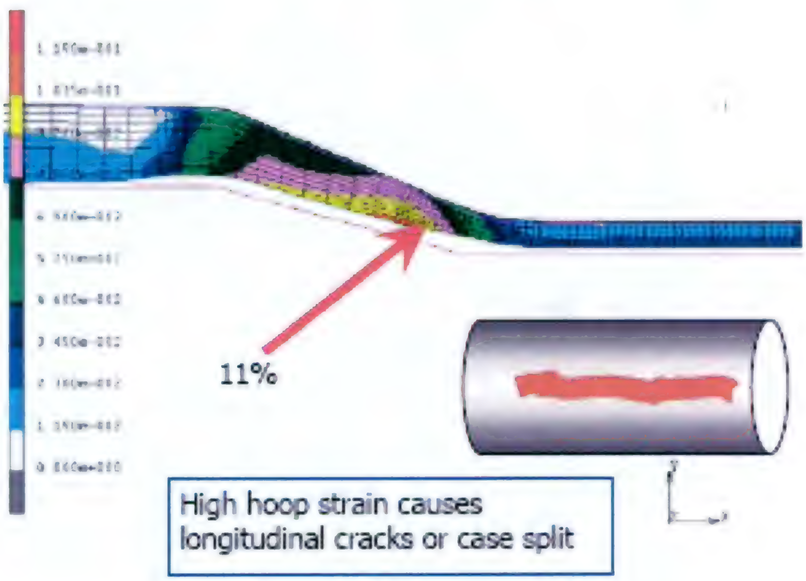
First, let's take a look at using strength as a material selection factor. To increase the strength of the polymer, one commonly adds glass fiber or carbon fiber into the polymer matrix. The tensile strength of polymer can be increased as high as 40,000 psi by adding 65% of glass fibers and can be up to 60,000 psi by using 60% of carbon fibers. The drawback of this approach is the elongation-to-break of these glass fiber filled polymer drops drastically to less than 3% for glass fiber filled polymer and less than 2% for carbon fiber filled polymer. This low elongation-to-break of the glass fiber filled polymer is a major weakness, since the marcroscope strain based on the clearance requirement between gun chamber and cartridge case is 2.9% in the nominal conditions and 4.9% in the worst scenario as shown in table 3. Moreover, the real strain under the ballistic pressure can be many times higher than these macroscope strains as shown in figures 3 (a) through (c) and 4 (a) through (c) from Frontier's finite element analysis on both 30% and 65% glass fiber filled polymer materials.

The principal strain of the polymer case made of the 30% glass fiber polymer under the ballistic pressure of 50,000 psi is shown in figure 3(a). Since the principal strain consists of hoop strain (which may cause longitudinal crack at the case mouth or case split) or longitudinal strain (which may cause circumferential crack), it is important to separate these two strains to identify the potential failure modes. The hoop strain and longitudinal strain of the polymer case made of

30% glass fiber filled polymer are shown in figure 3 (b) and (c), respectively. The Finite Element Analysis (FEA) simulation results indicate that both the longitudinal and hoop strains (11 to 18%) are much higher than the 2 to 4% elongation-to-break of the 30% glass fiber polymer. The polymer case will fracture into pieces at the neck, shoulder, and mouth areas.

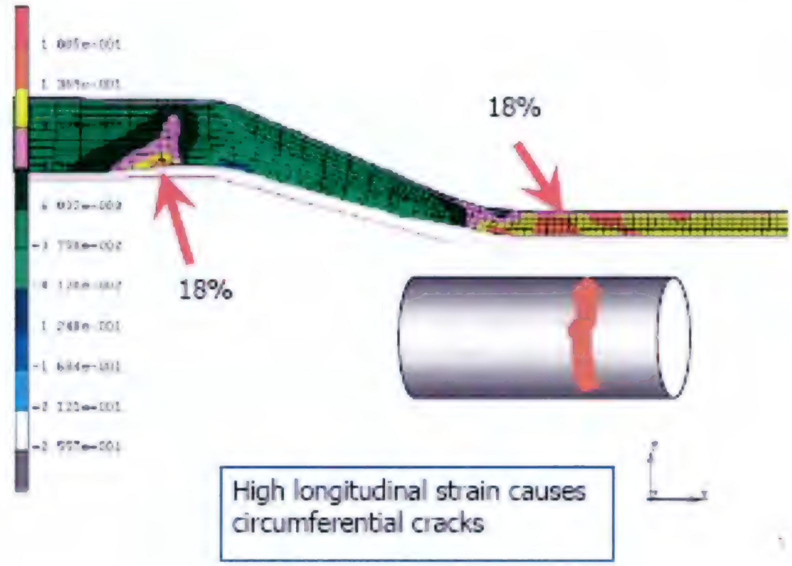


(a) Principal strain



(b) hoop strain

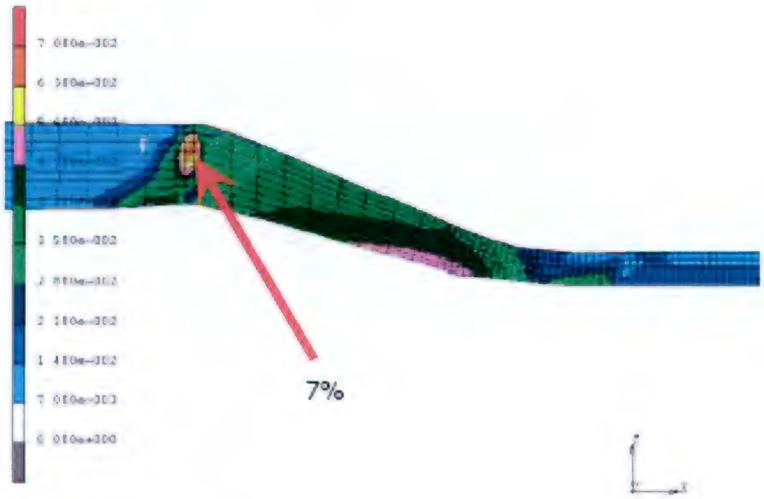
Figure 3
Polymer case made of the 30% glass fiber polymer under the ballistic pressure of 50,000 psi



(c)
longitudinal strain

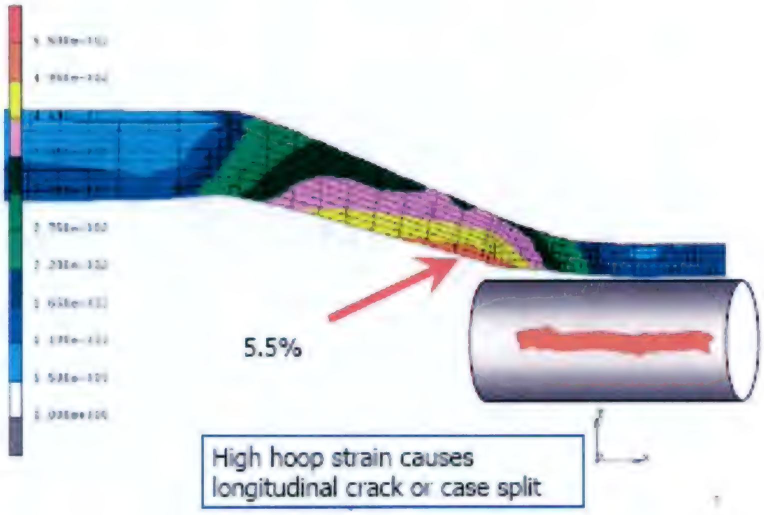
Figure 3
(continued)

If the glass fiber filled content is increased from 30% to 65%, its tensile strength is also increased from 25,000 psi to 40,000 psi. The principal, hoop, and longitudinal strains of the polymer case made of the high strength polymer from the FEA simulation results are shown in figure 4 (a) through (c).

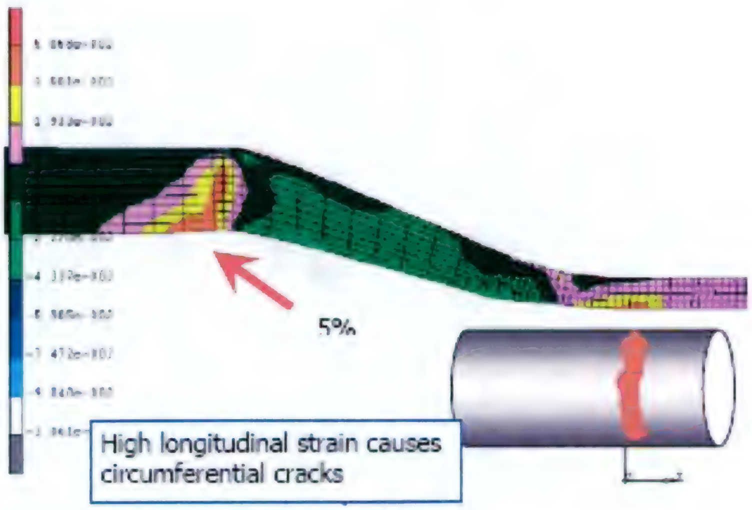


(a) Principal strain

Figure 4
Polymer case made of the 65% glass fiber polymer under the ballistic pressure of 50,000 psi



(b) hoop strain



(c) longitudinal strain

Table 4
(continued)

As the polymer becomes stronger, both hoop and longitudinal strains under the ballistic pressure becomes smaller, but nevertheless both strains are still higher than 2.5% elongation-to-break of the 65% glass fiber filled polymer. Thus, polymer case made of the 65% glass fiber filled polymer would fail and fracture.

It is important to point out that the mechanisms of two common failure modes of the polymer case can be predicted by the FEA simulation as shown in figures 3 and 4. The longitudinal crack is created at the location during the transition from case shoulder to case neck, and can result in case split as shown in figure 4(b). On the other hand, the circumferential crack is created at the location at the transition areas from the straight case body to the case shoulder as shown in figure 4(c). These observations can be confirmed by the failure modes of many test firings from the past polymer case developments.

Based on Frontier's extensive computer simulation studies, material development efforts and failures from the test firing results of other competing polymer case developments, Frontier concluded that high strength material, such as Parmax or glass fiber filled polymer, is not a good candidate material for polymer case application. On the other hand, in order to ensure the polymer case can survive the ballistic pressure, the material selection criterion should be ductile. One should use a ductile polymer for the case body, shoulder, neck, and mouth areas to ensure the polymer case can deform freely under the ballistic pressure without exceeding its elongation-to-break of the polymer. The integrity of the polymer case is then achieved through proper design to deliver the desired performances. Therefore, Frontier's polymer case is designed and built around Frontier's proprietary ductile polymer system to optimize its performance.

Figure 5 shows the FEA simulation results of the high stress case shoulder and neck areas for a polymer case made of ductile polymers. It reveals that the highly compressible ductile polymer will be subjected to higher deformation than glass fiber filled polymers under the ballistic pressure. Thus, it is important that the ductile polymer have high elongation-to-break at temperatures from -65°F to 165°F. It is a challenging task to find a high temperature polymer material that has an elongation-to-break consistently higher than 50% at the desired temperature range. Despite that fact, Frontier has proved that it is possible to modify high temperature engineering plastic to achieve high elongation.

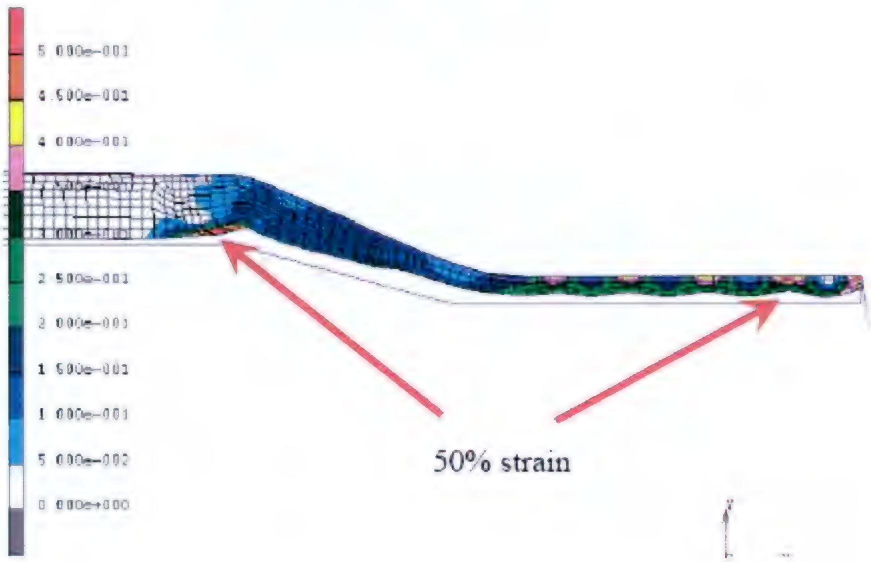


Figure 5
Tensile strain of the polymer case made of ductile polymer

Limitations of Conventional Injection Molding Process

Most of the small caliber plastic 5.56-mm ammunition cartridge cases do not achieve the same amount of interior volume as the brass case. Its interior volume loss is estimated to be as high as 15 to 20%. The primary reason for this lack of interior volume of plastic cartridge case is due to the inherent limit of the injection molding process. The conventional injection molding process has at least two constraints on the wall thickness of the polymer cartridge case, such as design limitation and thin wall molding limitation that hinder its performance.

Part Design Limitation

Since the molded parts must be able to be ejected from the mold cavities, in general, a draft angle (from 0.5 to 2 deg depending upon the material's mold shrinkage) has to be incorporated into the part design to ensure the part can be successfully and reliably ejected. For a tubular shape part like the 5.56-mm polymer cartridge case, its outside wall has a roughly 0.5 deg taper according to the M855 case specification, which is good for injection molding. However, the inside wall surface also needs a taper (or draft angle) to be at least 0.5 deg for high shrinkage polymers like polyamide in order for the metal core to be retracted for ejection. To the competing two-piece metal-plastic hybrid case design, the thickness of the plastic case body needs to be thicker to accommodate the requirements of the metal-plastic snap-fit joint. This design limit will place a constraint on the overall wall thickness to more than 0.030 in., and causes a large interior volume loss up to 15%. Consequently, this large interior volume loss will have a detrimental effect on the ballistic performance and shall be kept to a minimum. However, the attempts to reduce the wall thickness by reducing the wall thickness at the joint will weaken the joint and further lower the pull strength.

Thin Wall Molding Limitation

The second limitation of the conventional injection molding is the difficulty of the polymer melt flowing through the mold cavities with very thin wall thickness as shown in figure 6.

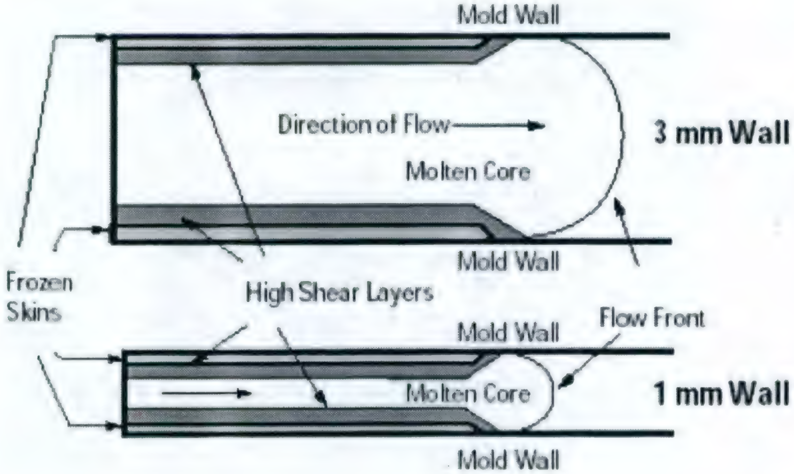


Figure 6
Melt flow pattern inside the thick and thin wall molding

In order to achieve the same interior volume of the M855 brass case, the wall thickness of the polymer case has to be about 0.010 in. (0.25 mm), which would poses a tremendous challenge for injection molding to meet this goal. Figure 6 shows the schematics of the polymer melt flow inside the parts with thick and thin wall thickness. As the wall thickness reduces, the heat will transfer more quickly, which will cause the polymer melt freeze off more quickly and significantly reduce the flow length. In general, it is easy to mold a part with a flow length/thickness (L/D) ratio as high as 250 for a part with a thickness of 0.125 in. (3 mm) by using high flow grade polymer. However, it would need a very high injection pressure molding machine to mold a part with a L/D ratio of 200 when its thickness reduces to 0.040 in. (1.0 mm). As a general rule of injection molding, the reduced flow length to wall thickness (L/D) ratio of a polymer is gradually reduced as the wall thickness decreases; however, the effects of the wall thickness on the L/D ratio become more significant once the wall thickness is below the critical wall thickness. The relationship between critical L/D ratio and wall thickness from the conventional injection molding at the constant injection pressure can be seen in figure 7.

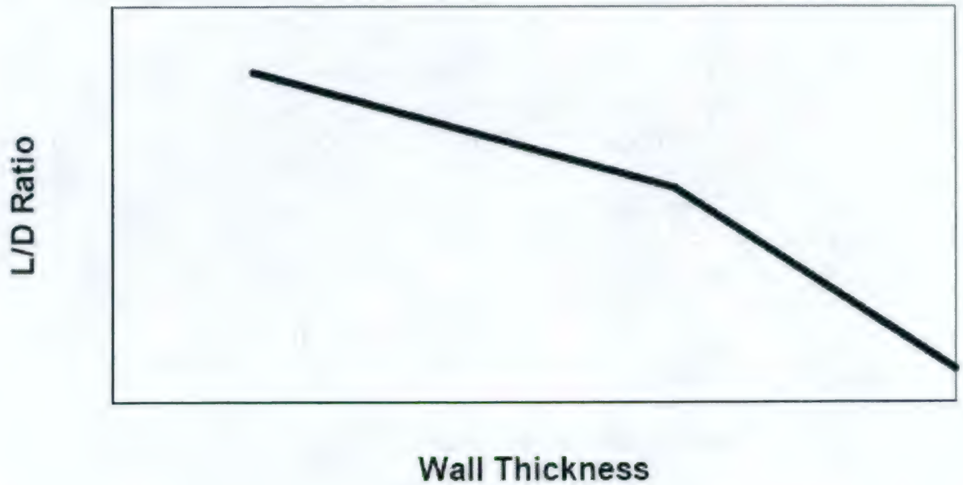


Figure 7
Critical flow L/D ratio of the polymer melt versus wall thickness at the constant injection pressure of injection molding

The length of the 5.56-mm polymer ammunition cartridge case, excluding the case head area, is roughly about 1.5 in. long. If the wall thickness is 0.030 in., which is used for most of the polymer 5.56-mm cartridge case developments, the L/D ratio would be 50:1, which is still feasible for injection molding using high flow polymers. However, the L/D increases to 150 if the wall thickness is reduced to 0.010 in., and the extra thin wall combined with the high L/D ratio makes it almost impossible for injection molding even with a state-of-the-art injection molding machine and very high flow polymer. For all that, the excessive molded-in stress may cause problems for the long-term dimension stability.

Frontier's Solutions

The competitive advantages of Frontier's solutions are to overcome the common failures by:

- Selecting a high temperature engineering plastic material that has upper temperature resistance more than 480°F, so that the polymer case can survive after cook-off in the hot gun chamber.
- Selecting a high temperature engineering plastic material with excellent ductility so that the polymer case will not crack or split under the ballistic pressure.
- Designing an unique one-piece polymer ammunition cartridge case reinforced with metal insert
- Proposing a fabrication process to produce the one-piece polymer case without the needs of adhesive bonding, mechanical fastening, or welding. Thus, the polymer case would have very high pull strength to ensure no case separation to cause the weapon to malfunction.

CONCLUSION – EFFECTIVE SOLUTION TO THE ISSUE

Significance of the Problem

Advances in weapon systems have resulted in the soldiers carrying additional gear to enhance combat effectiveness, but at the cost of increased weight. To ensure that America's soldiers maintain their overwhelming combat edge into the 21st century, making the load lighter for the soldier has moved to the top of the priority list in the Army. One of the heaviest pieces of load for soldier is the ammunition. This is because existing cartridge cases for rifles and machine guns are made with brass, which is heavy.

The U.S. military has tried numerous times since the 1950s to develop a lightweight ammunition cartridge case using polymers, so far, the efforts have fallen short. The most common failures of the polymer case include case cracks (either longitudinal cracks or circumferential cracks), case separation, propellant incompatibility, poor ballistic performance (low muzzle speed), case failed to be extracted after cook-off, and case shattered at low temperature.

The competitive advantage of Frontier's proposed advanced lightweight material and processing technologies will provide a one-piece polymer ammunition cartridge case that achieves 23% per cartridge weight savings and overcomes all the drawbacks seen in the past and current competing polymer cases.

Issues of Existing Polymer Cases

The baseline technology for the polymer case developments is derived from a two-piece metal-plastic hybrid design. A polymer (either high impact modified or glass fiber filled polymers) case body is snap-fitted to a brass (or ceramics) case head. This approach has several major drawbacks:

1. Poor reliability of the case integrity – the case integrity of the existing metal-plastic hybrid case design relies on a snap-fit to hold the plastic case body with the metal head. The reliability of the snap-fit may not meet the stringent demands of military ammunition requirements. Any defect on the snap-fit of the case design can have disastrous consequences of causing the weapon to malfunction during combat.

2. Case has too low pull strength – insufficient pull strength is achieved through snap-fit, and worst of all, the limited pull strength of the snap-fit drops rapidly at hot gun chamber due to loss of the shear strength at high temperatures.

3. Material lacks of ductility – polymer materials used in the exiting polymer cases do not have sufficient ductility that allows polymer to deform under high ballistic pressure. It results in a longitudinal crack at the case mouth or neck area, or circumferential crack at the case body. This problem is magnified at low temperatures; in particular, the shoulder, neck, and mouth areas of most existing polymer cases shattered to small pieces and may cause the weapon to malfunction.

Project Findings and Frontier's Approaches

To tackle the major root causes associated with more than 90% of failures seen in the past polymer case demonstrations, Frontier uses the advanced polymer processing technologies to develop a one-piece polymer case reinforced with metal insert in the case head. The one-piece case design completely eliminates the potential weakness of the metal-plastic joint and ensures the case integrity, particularly at the cook-off temperature. To provide support at the case head in the unsupported gun chamber area, the polymer case head is reinforced with a metal insert.

To produce the polymer case in one single piece, Frontier proposed to use the lost-core injection molding process with the sequential co-injection molding technique. This fabrication process would not only produce polymer cases in a single process, but also allow first injecting high strength glass fiber polymer in the case head, and subsequently injecting ductile polymer to fill the shoulder, neck, and mouth areas.

To ensure the polymer case survives the ballistic pressure at the desired temperature range of -65 to 165°F, Frontier has selected two of its proprietary polymer systems; a high strength 60% glass fiber filled polymer and a ductile polymer. This high strength polymer combined with the metal insert was analytically proven to survive the ballistic pressure. The ductile polymer exhibits high elongation-to-break, which well exceeds the maximum strain requirement at the case shoulder areas as predicted by the finite element analysis simulation.

Anticipated Benefits of the One-Piece Polymer Case

Frontier's one-piece polymer ammunition cartridge case is a state-of-the-art innovative technology involving a sound engineering design concept, advanced performance plastic, composite materials know-how and hands-on experiences in plastic fabrication processes to deliver desired ballistic, performance and long-term reliability results in the existing weapons. Frontier's innovative cartridge case design is expected to deliver the following benefits over other competing lightweight case designs:

- Deliver more than 20% weight saving
- Retain 90-95% interior volume
- Improved reliability in sandy regions
- Superior resistance to case cracking and splitting
- High pull strength – resistant to case separation
- Better resistance to cook-off
- Cost competitive to brass case

The significant benefits of this versatile lightweight, cost-effective and performance polymer-cased ammunition not only enables the soldier to lighten the load that is carried into battle and increase the lethality and survivability of all weapons, but also supports the Army's objectives for efficiency and cost effectiveness and makes it a winner with leaders, logisticians, and soldiers alike.

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